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An Open-Circuit Fault Diagnosis Method Based on Adjacent Trend Line Relationship of Current Vector Trajectory for Motor Drive Inverter

Xianrui Sun, Naizhe Diao, Chonghui Song *, Yunlong Qiu and Xiaolong Zhao 

College of Information Science and Engineering, Northeastern University, Shenyang 110819, China; 1910242@stu.neu.edu.cn (X.S.); diaonaizhe@ysu.edu.cn (N.D.)

* Correspondence: songchonghui@ise.neu.edu.cn

Abstract: This paper proposes a power switch open-circuit (OC) fault diagnosis method for a motor drive inverter system. This method utilizes adjacent trend lines to extract fault features from the current vector trajectory, enabling rapid fault diagnosis and localization. Firstly, the current vector trajectory is obtained by applying the Clark transformation to the three-phase currents, and trend line slopes are calculated using equidistant current signal nodes. Subsequently, the method determines fault by calculating changes in adjacent trend line slopes and quickly locates the faulty power switch by considering the average slope of adjacent trend lines and the beta-axis current direction in the alpha-beta coordinate system. Accurate OC fault localization can be achieved with just a few trend line data points calculated in each current cycle, reducing the extra hardware and computational burden. This method is not only suitable for load variations but also applicable to the diagnosis of both single-switch and multiple-switch faults. Finally, simulation and experimental results validate the effectiveness and robustness of the method.

Keywords: open-circuit fault; current vector trajectory; adjacent trend lines; load variation; multiple-switch fault; motor drive inverter



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1. Introduction

The widespread application of motor drive systems in industrial production can be attributed to the outstanding performance of inverters. As a result, the safe and stable operation of inverters plays a crucial role in enhancing the reliability of the entire motor drive system [1–5]. Therefore, power switch faults have become an increasingly prominent issue, significantly affecting the stable operation of inverters [6–9].

Generally, power switch faults are classified into two types: short-circuit (SC) and open-circuit (OC) faults [10]. During an SC fault, the abrupt increase in current immediately triggers the overcurrent protection circuit, leading to a rapid system shutdown. Conversely, the slow response characteristic of an OC fault typically prevents the system current from exhibiting an overcurrent condition, thereby not activating the overcurrent protection. If an OC fault goes undetected, long-term operation under this fault condition could result in increased current and voltage amplitudes, inflicting secondary damage on other functioning switches. This may even trigger an imbalance in the three-phase current, leading to motor overheating, which could ultimately cause motor damage [11].

In the recent research on OC faults in motor drive inverter systems, the dominant diagnostic approaches can typically be grouped into model-based, data-driven methods and signal-based methods [12,13]. Model-based methods employ observers to predefine the system model, subsequently executing fault diagnosis through the analysis of residual signals between actual and estimated signals [14–16]. A major drawback of model-based fault diagnosis method is that the effectiveness is heavily dependent on the accuracy of model parameters, which makes them less suitable for complex systems with varying

operating conditions [17]. Data-driven fault diagnosis algorithms utilize machine learning and artificial intelligence techniques to analyze historical and real-time data for detecting and diagnosing system faults [18–21]. Data-driven methods reduced reliance on accurate modeling, and the ability to learn from historical data to detect unknown faults. However, they also present drawbacks, including potential overfitting, sensitivity to data quality and quantity, and the requirement for large datasets and computational resources for training and validation [22].

Signal-based methods, including voltage-based and current-based methods, use measured signals to extract fault information features [23]. Some studies directly detect the voltage to determine OC faults. Ref. [24] proposed an IGBT OC fault diagnosis method based on the inverter voltage model. It used the error voltage obtained by comparing the actual voltage and command voltage, and the lower switch voltage. Ref. [25] uses a high-speed optocoupler to indirectly detect the voltage of the lower switch of the inverter and then performs the logic operation with the driving signal of the power switch to diagnose and locate the OC fault of the switch. Ref. [26] uses an instantaneous voltage error to diagnose IGBT OC faults. Refs. [27,28] used the instant bridge arm pole voltages and the instant bridge arm pole-to-pole voltages for fault diagnosis. With these methods, open-circuit faults can be detected as quickly as possible within one switching cycle. However, the need for additional ultra-high speed sampling circuits in these voltage-based methods are their main disadvantage, as it increases the cost, the design complexity and the point of failure of the system. In addition, when the inverter is under load, the noise generated by the high-frequency switch will greatly affect the accuracy of the voltage detection, so its accuracy cannot be guaranteed [29].

In comparison, current-based methods in signal-based approaches have the advantage of not requiring extra sensors, reducing costs and complexity, although the detection time is not as quick as voltage-based methods. Ref. [30] employs the normalization of current average value and absolute value methods to enhance the robustness of back-to-back converter open-circuit fault diagnosis. The technology of reconstructing three-phase currents in motor vector control systems is proposed in [31], with the aim to enhance diagnostic reliability in adverse environments. Some diagnostic methods based on signal processing, such as harmonic analysis, averaging, and waveform analysis, have been introduced [32]. The current vector trajectory approach has been proposed as one of the OC fault diagnostic steps in [33–36]. Specifically, ref. [33] introduced a fuzzy diagnosis method based on the stator current vector pattern in voltage source inverter motor drive systems. This approach extracts a fuzzy basis by analyzing current vector patterns under different fault conditions and then uses fuzzy logic to locate the faulty switch. However, due to the complexity of the pattern recognition required in its execution, it is not suitable for embedding into motor microcontrollers. In [34], Park's motor phase current vectors are used for fault detection in permanent magnet synchronous generator (PMSG) drivers. This method utilizes the derivative of the absolute Park vector phase to generate a reliable fault alarm signal for fault detection, also preventing transient misdiagnoses. In [35], the error of the Park vector normalized current average absolute value is used to enhance immunity to false alarms. Ref. [36] presents a novel phase loss fault diagnosis strategy for power drive systems based on second-order rotating Park transformations. Recently, several new signal-based diagnostic schemes have been proposed to enhance diagnostic time, robustness, or applicability. In [37], a new method based on current probability density analysis is proposed for inverter open-circuit fault diagnosis. Ref. [38] introduces a principle of low-frequency sampling for major fault components. This method uses a smaller set of sample data to reflect the characteristics of primary components under different switch combinations, thereby reducing the data volume needed for processing. Ref. [39] proposes an online identification method for three-phase inverter open-circuit faults based on phase current polarity and normalized line current. Ref. [40] presents a diagnostic approach based on reference current error, which is simple and fast but is not suitable for open-loop control systems. Ref. [41] proposes a fault diagnosis method based on the phase of current vector

trajectories, one which can achieve multiple-switch fault localizations. However, the use of standard deviation increases the computational complexity of the algorithm. While the aforementioned methods exhibit some advantages, fault detection takes a longer time. To shorten the diagnosis time, ref. [42] samples three-phase sinusoidal current signals, encodes the trend features by analyzing the trend relationship between adjacent sampling points, and locates faults by calculating the changes in the trend of the lines. Ref. [43] proposes a neural-network-like structure for diagnosing open-circuit faults in traction motor drive systems using dual current-time pairs. These two methods shorten the fault diagnosis time, but they are only applicable to single-switch fault diagnosis, which significantly limits their scope of application in industrial settings.

An OC fault diagnosis method for power switches in motor drive inverter systems is proposed based on calculating adjacent trend line slope differences of a current vector trajectory. By setting a detection threshold for adjacent trend line slope differences, OC faults can be detected, and the faulty power switch can be located using the adjacent trend line slope and the direction of current vector trajectory. The method can handle not only situations with varying loads but is also capable of diagnosing faults in both single-switch and multiple-switch OC fault scenarios while reducing the extra hardware and computational burden.

The remaining contents of this paper are organized as follows. The motor drive inverter system and OC fault analysis of the inverter is shown in Section 2. The OC faults diagnosis method is illustrated in Section 3. In Section 4, the simulation and experimental results validate the effectiveness of the proposed method. Finally, Section 5 gives the summary and some conclusions.

2. The OC Fault Analysis for Motor Drive Inverter System

The three-phase, two-level topology inverter structure for a motor drive system is shown in Figure 1, including DC source, three-phase two-level inverter, and motor. The inverter consists of six switches ($S_1 \sim S_6$) with six antiparallel diodes ($D_1 \sim D_6$). V_{dc} is the DC source voltage. i_a , i_b and i_c are the output phase currents.

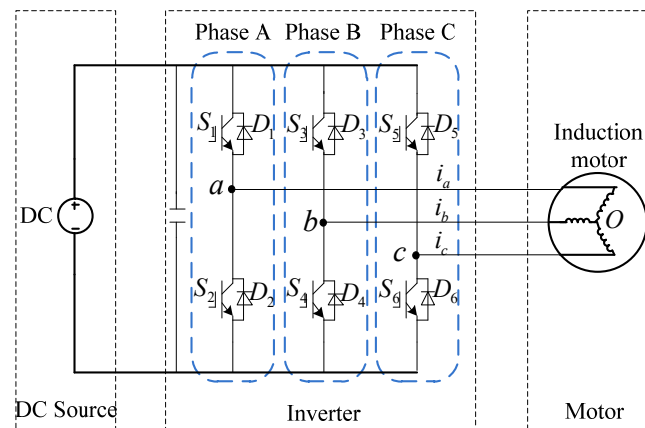


Figure 1. A three-phase, two-level topology inverter structure of motor drive system.

In general, the loads of the three phases are symmetrical

$$\begin{cases} i_a = I_m \cos(\omega t) \\ i_b = I_m \cos(\omega t + 2\pi/3) \\ i_c = I_m \cos(\omega t - 2\pi/3) \end{cases} \quad (1)$$

where I_m and ω are the amplitude and angular frequency of the phase currents, respectively.

Applying Kirchhoff's law, the phase currents satisfy the following equation.

$$i_a + i_b + i_c = 0. \quad (2)$$

When the OC fault occurs, the related power switch is disconnected and ceases to be controlled by the corresponding driving signal. This situation manifests a local feature where the continuity of pertinent signals is interrupted.

Generally, OC faults in inverters are divided into single-switch fault and multiple-switch faults. The output current feature of the inverter corresponding to the successive faults of switches S_1 and S_6 are illustrated as examples. As shown in Figure 2, the OC fault occurred in S_1 , which caused the current of phase A to be zero for half a period and the currents of phase B and phase C to be slightly deformed. After that, the OC fault also occurred in S_6 , so that both the currents of phase A and phase C have similar fault features of zero for half a period.

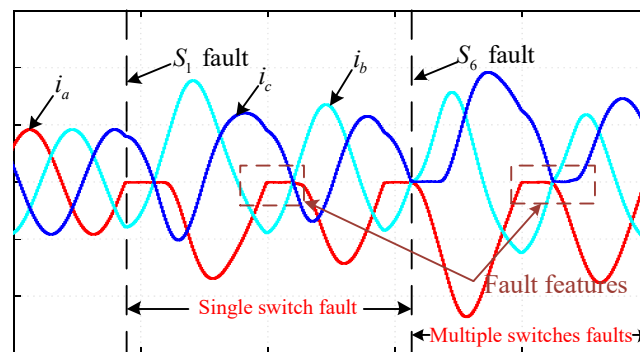


Figure 2. Fault features of single-switch fault and multiple-switch fault.

The majority of current-based methods currently available are focused on single-switch faults. While these can provide some level of system protection, they are ineffective when multiple switches fail, potentially resulting in a cascade of severe consequences.

3. Fault Diagnosis Analysis of the Proposed Method

3.1. Fault Feature Extraction of Adjacent Trend Lines

According to the current vector trajectory method [41], the three-phase current (1) is subjected to Clark transformation

$$\begin{cases} i_\alpha = \frac{2}{3} \left(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c \right) \\ i_\beta = \frac{2}{3} \left(\frac{\sqrt{3}}{2}i_b - \frac{\sqrt{3}}{2}i_c \right) \end{cases}, \quad (3)$$

therefrom, the three-phase current is transferred to the two-phase ($\alpha - \beta$) coordinate system.

Under normal steady-state conditions, the current vector trajectory is a circle in the $\alpha - \beta$ coordinate system. As shown in Figure 3, the complete circle represents a period of current. By dividing the circle into n equal parts, the trend line of the current vector trajectory is obtained.

The number of trigger time points is

$$N_p = T/T_t + 1, \quad (4)$$

where T is the fundamental wave period time and T_t is the trigger time of the data processing instruction.

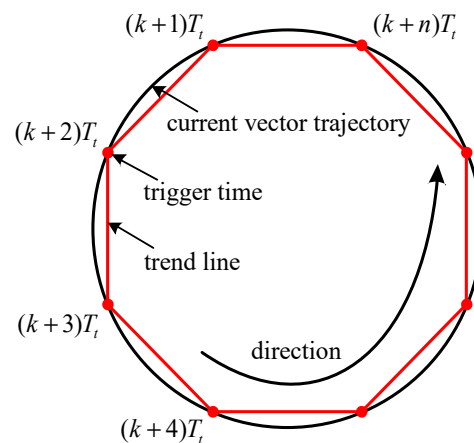


Figure 3. The current vector trajectory and uniformly spaced trend lines.

According to (3), the slope of the trend line of the current vector trajectory is

$$L_s(k) = \frac{i_\beta(kT_t) - i_\beta((k-1)T_t)}{i_\alpha(kT_t) - i_\alpha((k-1)T_t)}, \quad k = 0, 1, 2, \dots \quad (5)$$

Considering some possible failures, $L_s(k)$ tends to infinity, so the slope of the current vector trajectory is artificially set

$$L_s^a(k) = \frac{1}{L_s(k)}. \quad (6)$$

According to Figure 3, the trend line of the current trajectory can be approximated to a regular polygon inscribed in a circle, and the internal angle of this regular n -sided polygon is

$$\theta_{in}(n) = 180 * (n - 2) / n, \quad (7)$$

where n can be regarded as related to the trigger time point N_p , that is

$$n = N_p - 1. \quad (8)$$

Set two detection variables, which represent the slope angle of the current trend line and the slope angle of the previous trend line respectively, as follows

$$\begin{cases} T_l^k = \arctan(L_s^a(k)) * 180 / \pi \\ T_l^j = \arctan(L_s^a(k-1)) * 180 / \pi \end{cases} \quad (9)$$

At this time, the angle difference between adjacent current vector traces is about

$$D_{deg}(k) = T_l^k - T_l^j. \quad (10)$$

Under normal circumstances, the difference between the angles of adjacent trajectories is related to the internal angle of the regular polygon, which is approximately

$$D_{deg}^* = 180 - \theta_{in}(n). \quad (11)$$

However, when an OC fault occurs, the current vector trajectory changes and the difference between adjacent trajectories will also change.

3.2. Fault Detection Combined with Current Vector Trajectory Adjacent Trend Lines

As the motor drive system runs in a healthy state, the current vector trajectory is circular. When the OC fault occurs in any power switch, depending on fault location, the current vector trajectory presents different shapes, as shown in Figures 4 and 5.

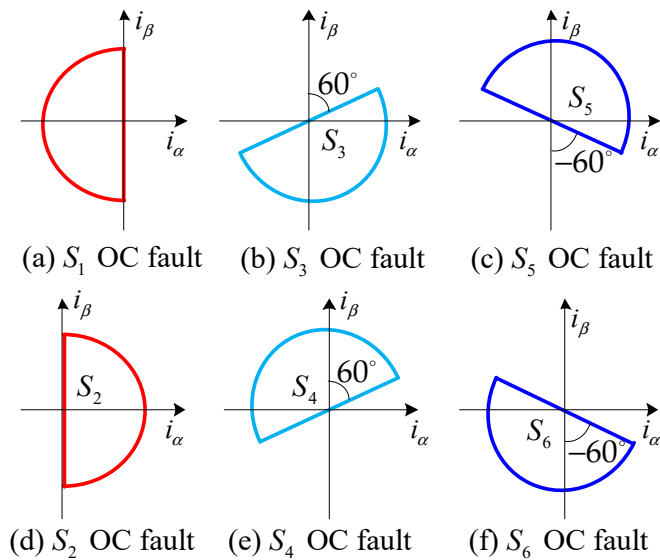


Figure 4. The current vector trajectory of a single-switch OC fault.

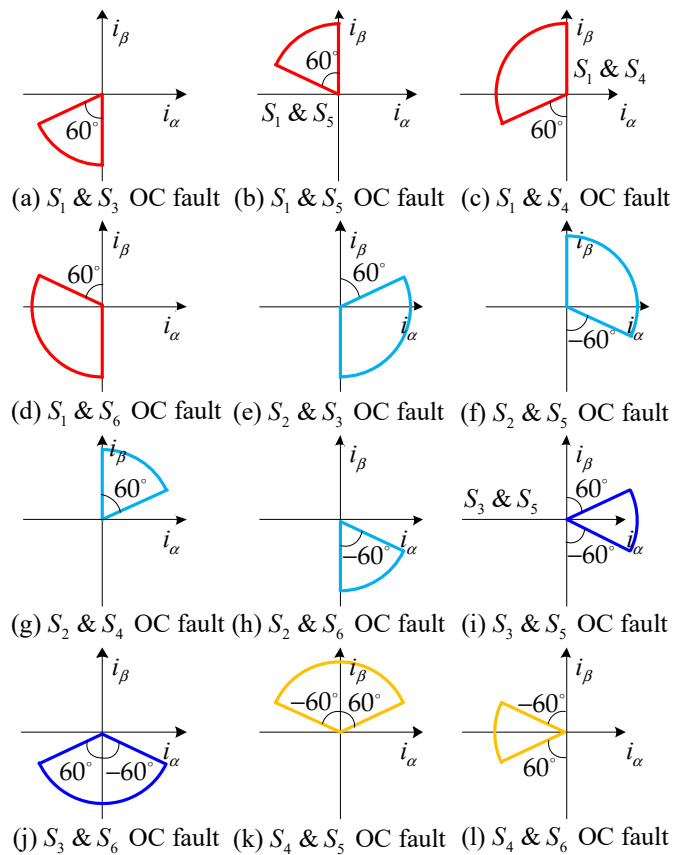


Figure 5. The current vector trajectory of a multiple-switch OC fault.

Figure 4 shows the occurrence of a single-switch OC fault in the inverter, the current vector trajectory will show a semicircle in different directions according to different fault locations.

As shown in Figure 5, when the multiple-switch OC fault occurs in the inverter, the current vector trajectory will no longer be a semicircle, but by combining the trajectories of the two fault locations in Figure 4, a new fan-shaped trajectory is obtained.

Although the shape of these fan-shaped trajectories seems to be inconsistent in size, the actual time required to pass these paths is the same, and they all represent a current trajectory of a fundamental period. Among these, the straight part during a single-switch fault accounts for about one-half of the period, and the straight part during a double switch fault accounts for about two-thirds of the period.

Therefore, the trajectory graph at the time of the fault is still divided according to the previous normal circle, which is divided into n equal parts at equal intervals.

When the OC fault occurs, regardless of whether it is a single switch or multiple switch situation, the slope difference of the trend line of the adjacent current vector trajectory of the straight-line part is approximately that of zero, which means

$$|D_{deg}(k)| \ll D_{deg}^*(n), \quad (12)$$

where $|\cdot|$ represents the absolute value symbol, so the threshold value of the fault can be determined according to the number n of equal intervals divided in advance, that is

$$Th = \mu * D_{deg}^*(n), \quad (13)$$

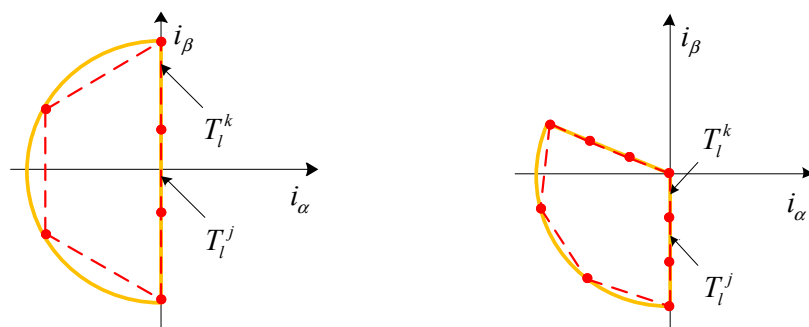
where μ is a number less than 1.

According to experience, this is generally 20–40%. In this way, a specific threshold is set aside to guarantee accurate fault detection when the phase current fluctuates.

$$R_{oc}(k) = \begin{cases} 1 & |D_{deg}(k)| < T_h \\ 0 & \text{other} \end{cases}, \quad (14)$$

R_{oc} is the diagnosis result of whether the system has the OC fault, where $R_{oc} = 1$ this indicates that an OC fault has occurred, and $R_{oc} = 0$ indicates that the system is operating under normal operation.

Because the OC fault diagnosis needs to be judged by the slope difference (angle difference) of the trend line, two trend lines are required for judgment in the straight-line area of the current vector trajectory. From Figure 6, the interval of three trend lines is reserved in the straight area to ensure that regardless of the situation, there are at least two complete trend lines in the straight area to ensure that the diagnosis can be carried out normally.



(a) Selection trend lines of S_1 OC fault (b) Selection trend lines of S_1 & S_6 OC fault

Figure 6. Selection of trend line of current vector trajectory.

From Figure 6a, we can see that, for a single-switch fault, the straight-line area occupies one-half of the entire cycle. The entire current vector trajectory must be divided into at least six equal parts according to the sampling time to ensure that there are three trend lines in the straight-line area. Additionally, in Figure 6b, each linear area in the event of a multiple-switch fault only occupies one-third of the cycle, so at least nine equal divisions must be made according to the sampling time to ensure that each linear area has three trend lines.

Since the fault diagnosis is performed according to the trend line of each segment, the more the number n of equal parts, the faster the detection speed will be. Correspondingly, the smaller the data interval selected by the trend line, the greater the impact of current fluctuations. Conversely, the smaller the number n of equal intervals, the less the amount of data that needs to be calculated, but the time required for diagnosis will be longer. Therefore, a reasonable selection of equal intervals is necessary, and it is generally appropriate that the straight-line area of the fault contains 2~4 trend lines.

3.3. Fault Location

For fault location, the average value of T_l^k and T_l^j is usually selected as the diagnostic variable, which is

$$S_l^\alpha = \frac{1}{2}(T_l^k + T_l^j) \pm \varepsilon. \quad (15)$$

where, ε is defined as the deviation threshold.

Here, S_l^α can judge which of the three phases has a fault. As shown in Figures 4 and 5, the current vector trajectory under single-switch and multiple-switch OC faults determines whether there are three threshold angles in the linear region, namely 0° , -60° and 60° . To mitigate the impact of fluctuations in the current sample values, ε is defined as the fluctuation range for S_l^α . In this case, one-sixth of the absolute value of the threshold is chosen as the upper limit for fluctuation.

Next, based on the direction of the current vector trajectory, it is necessary to determine whether it is an upper switch fault or a lower switch fault. Here, the difference in i_β of the trend line endpoints is used to ascertain the direction of the current vector trajectory, thereby identifying the missing current segment within a cycle and locating the faulty power switch.

$$D_i^\beta = \begin{cases} 1, & i_\beta(k) - i_\beta(k-1) > \sigma \\ -1, & i_\beta(k) - i_\beta(k-1) < \sigma \end{cases} \quad (16)$$

where σ is the current deviation threshold.

Under ideal conditions, the value of threshold σ is zero. However, considering the effects of noise and measurement errors, σ should be chosen as a value close to zero. After multiple simulations and experimental analyses, σ is set to 0.01. Then, by comparing S_l^α with predefined angles and by simultaneously determining the sign of D_i^β , the fault location can be identified.

The diagnosis rule for a single-switch fault is shown in (17). After the OC fault occurs, the fault diagnosis variables $FT_{ij}(i = a, b, c; j = 1, 2)$ are fixed and can be maintained until the fault is isolated in practical engineering.

$$\left\{ \begin{array}{l} FT_{a1} = \begin{cases} 1, & R_{oc} = 1 \text{ and } S_l^\alpha = 0^\circ \text{ and } D_i^\beta > 0 \\ 0, & \text{else} \end{cases} \\ FT_{a2} = \begin{cases} 1, & R_{oc} = 1 \text{ and } S_l^\alpha = 0^\circ \text{ and } D_i^\beta < 0 \\ 0, & \text{else} \end{cases} \\ FT_{b1} = \begin{cases} 1, & R_{oc} = 1 \text{ and } S_l^\alpha = 60^\circ \text{ and } D_i^\beta < 0 \\ 0, & \text{else} \end{cases} \\ FT_{b2} = \begin{cases} 1, & R_{oc} = 1 \text{ and } S_l^\alpha = 60^\circ \text{ and } D_i^\beta > 0 \\ 0, & \text{else} \end{cases} \\ FT_{c1} = \begin{cases} 1, & R_{oc} = 1 \text{ and } S_l^\alpha = -60^\circ \text{ and } D_i^\beta < 0 \\ 0, & \text{else} \end{cases} \\ FT_{c2} = \begin{cases} 1, & R_{oc} = 1 \text{ and } S_l^\alpha = -60^\circ \text{ and } D_i^\beta > 0 \\ 0, & \text{else} \end{cases} \end{array} \right. \quad (17)$$

The fault diagnosis flow chart of the proposed method is presented in Figure 7.

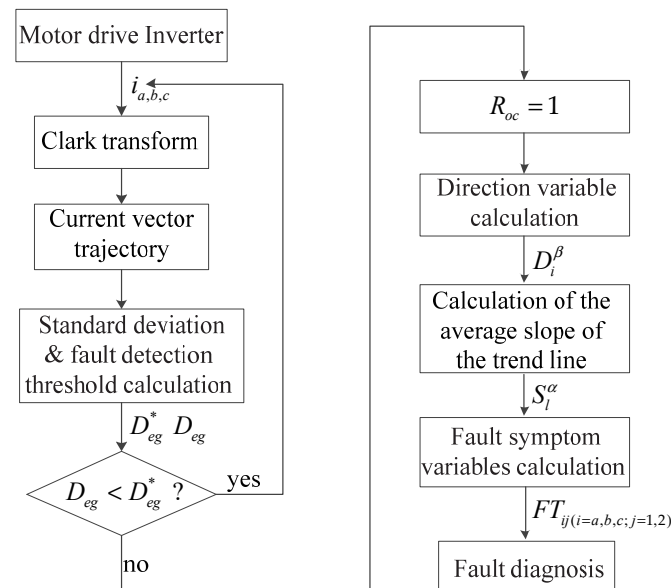


Figure 7. Fault diagnosis flowchart based on the adjacent trend line of current vector trajectory.

The relationship between diagnostic variables and faulty switches is displayed in Table 1.

Table 1. Relationship between diagnostic variables and faulty switches.

Fault Type	Fault Location	FT_{a1}	FT_{a2}	FT_{b1}	FT_{b2}	FT_{c1}	FT_{c2}
Single-switch OC fault	S_1	1	0	0	0	0	0
	S_2	0	1	0	0	0	0
	S_3	0	0	1	0	0	0
	S_4	0	0	0	1	0	0
	S_5	0	0	0	0	1	0
	S_6	0	0	0	0	0	1

Table 1. Cont.

Fault Type	Fault Location	FT_{a1}	FT_{a2}	FT_{b1}	FT_{b2}	FT_{c1}	FT_{c2}
Multiple-switch OC Faults	S_1S_3	1	0	1	0	0	0
	S_1S_4	1	0	0	1	0	0
	S_1S_5	1	0	0	0	1	0
	S_1S_6	1	0	0	0	0	1
	S_2S_3	0	1	1	0	0	0
	S_2S_4	0	1	0	1	0	0
	S_2S_5	0	1	0	0	1	0
	S_2S_6	0	1	0	0	0	1
	S_3S_5	0	0	1	0	1	0
	S_3S_6	0	0	1	0	1	0
	S_4S_5	0	0	0	1	1	0
	S_4S_6	0	0	0	1	0	1

4. Simulation and Experiment Results

The effectiveness of the proposed fault diagnosis method is verified by the simulation and the experiment.

4.1. Simulation Results Analysis

A simulation is established in MATLAB based on the two-level motor drive inverter system, as shown in Figure 1. The load consists of a 4 kW induction motor with a rated voltage of 380 V and a rated current of 10.7 A. The output frequency of the inverter is set at 50 Hz. Other simulation parameters are $T = 20$ ms, $T_t = 2$ ms and $n = 10$. By terminating the corresponding driving signal, the OC fault is simulated.

4.1.1. Single-Switch OC Fault Diagnosis Simulation Results

Figure 8 shows the simulation results for the S_3 OC fault. Figure 8a presents the three-phase currents, while Figure 8e shows the diagnosis result. Figure 8b, Figure 8c, and Figure 8d respectively represent the variable values in the fault diagnosis process, namely R_{oc} , S_l^α and D_i^β . In Figure 8a, when the fault occurs at 1.244 s, the phase B current is distorted from a full sinusoidal wave to a half-sine wave, leaving only the lower half of the waveform. As seen in Figure 8b, at 1.25 s, R_{oc} changes from 0 to 1, indicating the occurrence of a switch fault. At this point, S_l^α equals 60° , and $D_i^\beta < 0$. In Figure 8e, the value of S_3 shifts from 0 to 3, successfully detecting the upper switch fault in phase B with an approximate detection time of 6 ms.

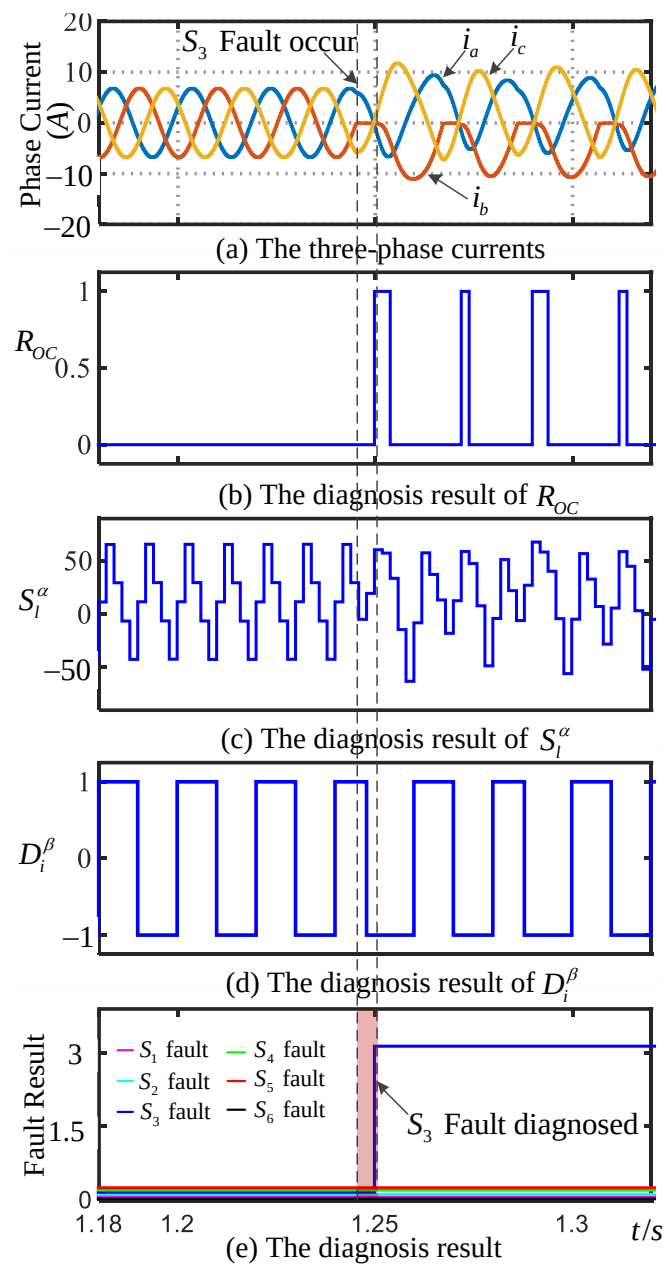


Figure 8. The simulation results of S_3 OC fault.

4.1.2. Multiple-Switch OC Fault Diagnosis Simulation Results

Figure 9 presents the simulation results for the S_3 and S_6 faults occurring at different times. Figure 9a illustrates the three-phase currents, while Figure 9e depicts the diagnostic results. Figure 9b, Figure 9c, and Figure 9d respectively represent the variable values in the fault diagnosis process, namely R_{OC} , S_l^α and D_i^β . In Figure 9a, when the fault occurs at 1.224 s, the phase A current distorts from a full sinusoidal wave to a half-sine wave, with only the lower half of the waveform remaining. As seen in Figure 9b, at 1.23 s, R_{OC} changes from 0 to 1, indicating the occurrence of a switch OC fault. At this point, S_l^α equals 60° , and $D_i^\beta < 0$. In Figure 9e, the value of S_3 shifts from 0 to 3, successfully detecting the upper switch fault in phase B with an approximate detection time of 6 ms.

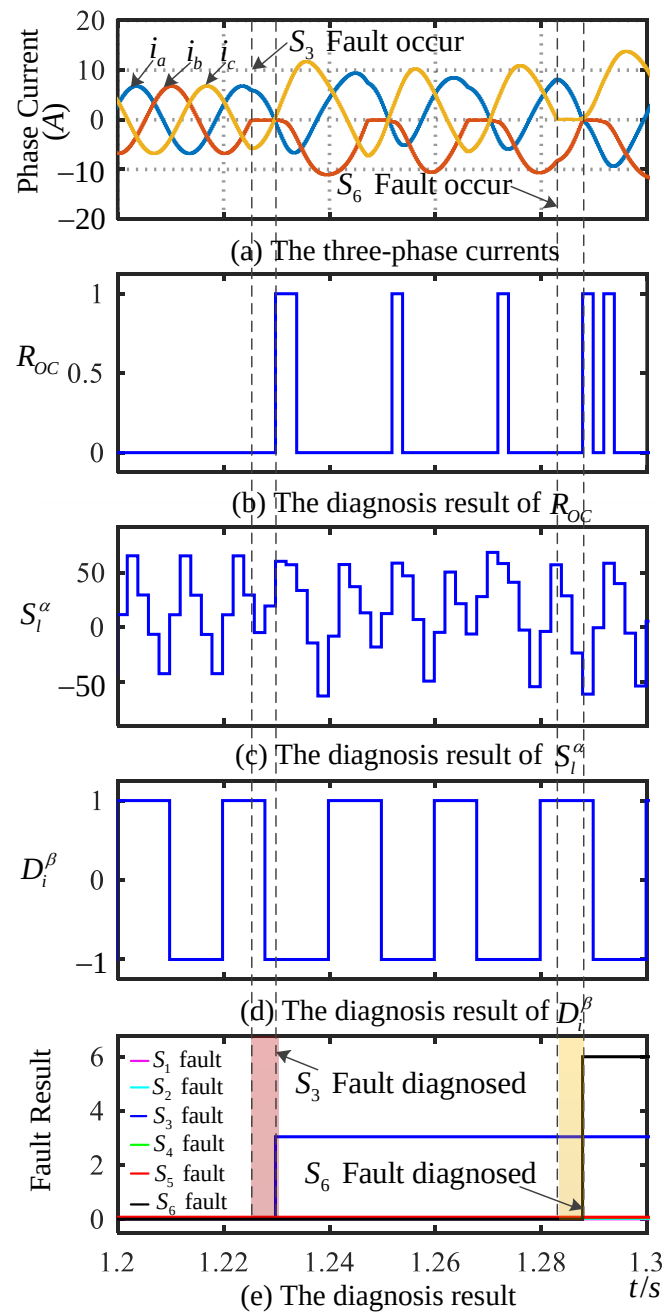


Figure 9. The simulation results of S_3 and S_6 OC fault.

Subsequently, when another fault occurs at 1.282 s, the phase B current distorts from a full sinusoidal wave to a half-sine wave, with only the upper half of the waveform remaining. As seen in Figure 9b, at 1.29 s, R_{oc} transitions from 0 to 1, indicating a switch fault. At this point, S_l^α equals -60° , and $D_i^\beta > 0$. In Figure 9e, the value of S_6 moves from 0 to 6, successfully detecting the lower switch fault in phase C with an approximate detection time of 8 ms.

4.1.3. Simultaneous OC Faults of S_1 and S_4 Diagnosis Simulation Results

Figure 10 shows the diagnosis process in the case of simultaneous open-circuit faults on the upper switch S_1 of phase A and on the lower switch S_4 of phase B. Figure 10a illustrates the three-phase currents, while Figure 10e depicts the diagnostic results. Figure 10b, Figure 10c, and Figure 10d respectively represent the variable values in the fault diagnosis

process, namely R_{oc} , S_i^α and D_i^β . Similar to the previous case, for the inverter in a healthy condition, the fault output variables are null. When the simultaneous open-circuit faults occur on S_1 and S_4 at 1.255 s, the phase A current consequently distorts from a full sinusoidal wave to a half-sine wave, with only the upper half of the waveform remaining. Meanwhile, the phase B current distorts from a full sinusoidal wave to a half-sine wave, with only the lower half of the waveform remaining. From Figure 10b, it can be seen that R_{oc} changes from 0 to 1 at 1.263 s and 1.26 s, respectively. Correspondingly, S_1 shifts from 0 to 1 and S_4 shifts from 0 to 4, which indicates simultaneous OC faults on S_1 and S_4 . Furthermore, the faulty switch is diagnosed within 8 ms, about 40% of the current cycle.

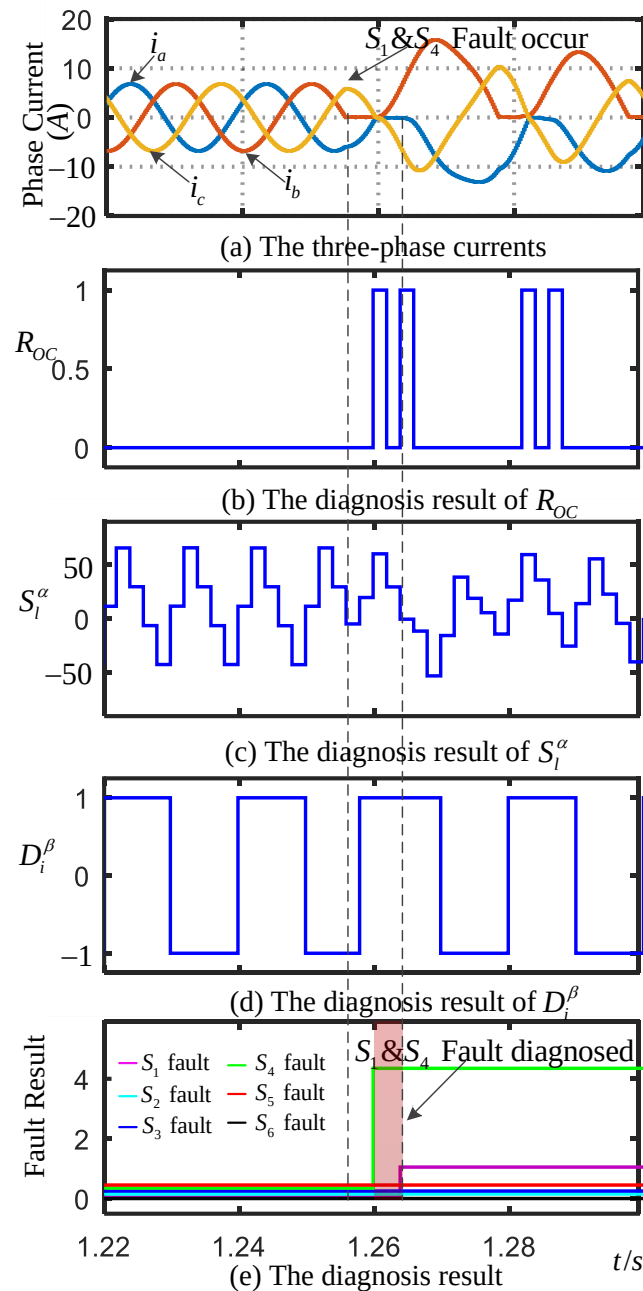


Figure 10. The simulation results of S_1 and S_4 simultaneous OC faults.

As shown in Figures 8–10, the fault diagnosis results are accurate and consistent with the theoretical analysis. Meanwhile the diagnosed times are both less than 8 ms.

4.2. Experimental Results Analysis

As shown in Figure 11, this paper establishes an experimental platform for a motor drive system based on a two-level topology to validate the accuracy and effectiveness of the proposed method. The control system uses Altera's FPGA EP4CE10E22C8 to complete the operation of the fault diagnosis algorithm. The power switch IGBT is an Infineon FF50R12KT4 and the OC faults are simulated by removing the corresponding drive signal. The output current and diagnostic indicator signals are captured by oscilloscope.

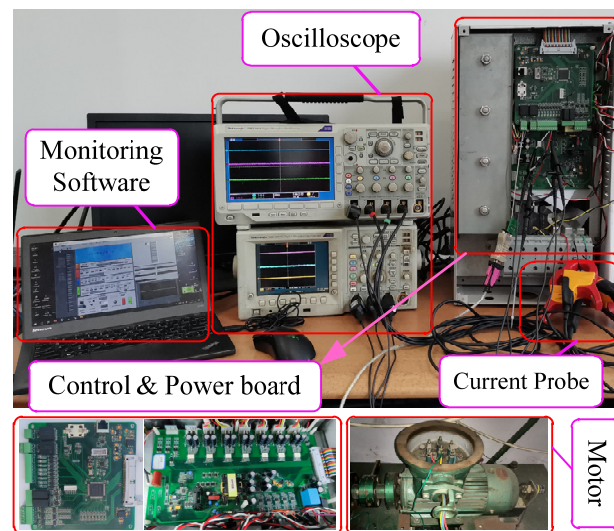


Figure 11. Experimental platform.

The parameters of the experiment are shown in Table 2.

Table 2. The experimental parameters.

Parameters	Symbol	Value
DC bus voltage	V_{dc}	540 V
Motor rated power	P	2.2 kw
Motor rated voltage	V	380 V
Motor rated frequency	f	50 Hz
Motor rated current	I	5.8 A
Pole logarithm	p	2

Figures 12–14 show the diagnostic results of different OC faults in the inverter when the motor is operating at the rated frequency.

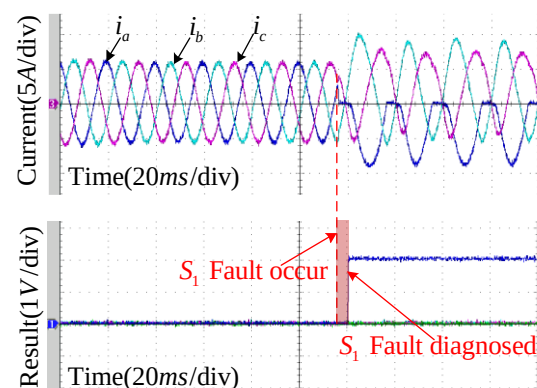


Figure 12. The experimental results of S_1 OC fault.

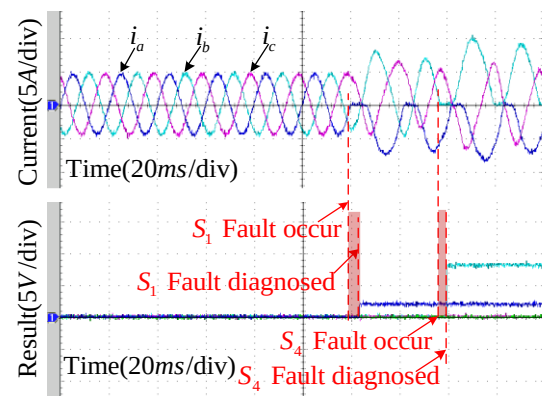


Figure 13. The experimental results of S_1 and S_4 OC fault.

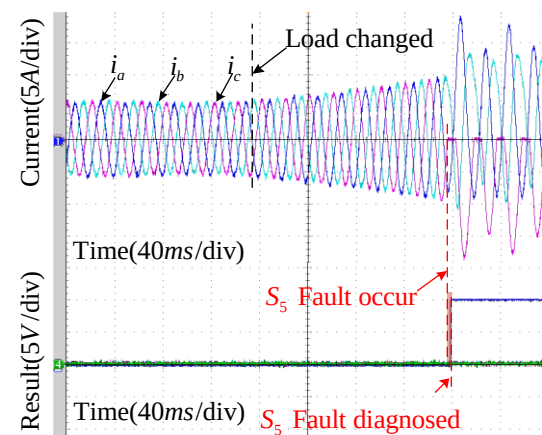


Figure 14. The experimental results of the S_5 OC fault under load change condition.

In Figure 12, the algorithm requires only 6 ms to detect and locate a single-switch fault, specifically when the upper switch S_1 of phase A experiences the OC fault.

In Figure 13, there are multiple-switch faults that occur on the phase A upper switch S_1 and the phase B lower switch S_4 at different times. The method is capable of detecting the first occurrence of a fault and subsequently detecting the second fault, enabling the location of the multiple-switch faults with a detection time of less than 8 ms.

When the motor load in Figure 14 increases, it leads to a change in the current amplitude. Upon the occurrence of an OC fault in the phase C upper switch S_5 , the method takes approximately 8 ms from the detection of fault-related current features to the diagnosis and location of the fault. The experimental results align with both the simulation results and the theoretical expectation.

4.3. Compared with Other Methods

In order to further verify the performance of the proposed method, in consideration of the question as to whether the method can fit for load changes, computational complexity, the multiple-switch OC faults, the average diagnosis time, etc., a comparison with other methods is shown in Table 3.

Table 3. Comparison of the proposed method with other methods.

Research Algorithms	[23]	[24]	[21]	[43]	Proposed Method
Consider load variation	yes	no	yes	yes	yes
Consider multiple-switch faults	no	yes	yes	no	yes
Parameter sensitivity	yes	no	no	no	no
Computational complexity	medium	low	high	low	low
Extra hardware circuit	no	yes	no	no	no
Diagnosis time	<0.5 <i>T</i>	<0.1 <i>T</i>	>6 <i>T</i>	<0.4 <i>T</i>	<0.4 <i>T</i>

From Table 3, the proposed method can quickly diagnose faults within 2/5 cycle. Compared with other current-based diagnosis methods [43], it can be applied to multiple-switch faults. Compared with the voltage-based methods, such as [24], though it has the fastest diagnostic speed and highest accuracy, it needs additional voltage sensors or detection circuits, which increases the cost and failure points.

In addition, the data-driven methods [21] require a large amount of historical data for training, which requires a long diagnosis time. Although the diagnostic accuracy is high, it is difficult to use in the real-time diagnosis process due to its high computational burden.

Furthermore, the proposed method is insensitive to parameter changes and is suitable for multiple fault detection compared with the model-based method [23].

Above all, the proposed method needs only the current signal and does not depend on the model parameters. Furthermore, even with load variations, this method can still accurately detect faults. Moreover, it can diagnose single-switch faults and multiple-switch faults without adding additional hardware and it can be widely used on most engineering occasions.

5. Discussion

In addressing the issue of power switch OC faults in motor drive inverters, this paper introduces a diagnostic method based on adjacent trend lines. The motion characteristics of the current vector trajectory form the key concept in constructing adjacent polyline trend relationships. By utilizing adjacent trend lines to extract fault features, calculating the slope changes of these lines for fault determination, and swiftly pinpointing the faulted switch based on the beta-axis current direction, this method achieves rapid fault diagnosis. This only requires the computation of a small amount of current signal node information, resulting in a relatively low computational burden. Furthermore, this method exhibits strong robustness against load variations and is applicable for diagnosing multiple-switch faults. Additionally, it can be widely used in various AC induction motor drive applications.

It is a common characteristic that each method has its limitations. The method proposed in this paper demonstrates that optimizing the trend line selection strategy can further enhance the diagnostic time of this method. Moreover, this method has only implemented fault diagnosis for a two-level inverter topology. For use with other inverter topologies, specific modifications to the fault localization method are needed in order to achieve non-intrusive OC fault detection.

Lastly, a technique rooted in artificial intelligence is being actively explored. The outcomes of this research will be shared in an upcoming publication. Notably, this method is no longer dependent on specific inverter drive topologies to ascertain the occurrence of faults. It also offers the capability to evaluate in advance whether a fault may occur, based on performance status.

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